Contract-Based Integration of Cyber-Physical Analyses

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October 14, 2014
14th International Conference on Embedded Software

Carnegie Mellon
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Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **07 NOV 2014**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Contract-Based Integration of Cyber-Physical Analyses**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Dionisio de Niz Ivan Ruchkin; Sagar Chaki; David Garlan**	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Software Engineering Institute Carnegie Mellon University Pittsburgh, PA 15213**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**28**	

This material is based upon work funded and supported by the Department of Defense under Contract No. FA8721-05-C-0003 with Carnegie Mellon University for the operation of the Software Engineering Institute, a federally funded research and development center.

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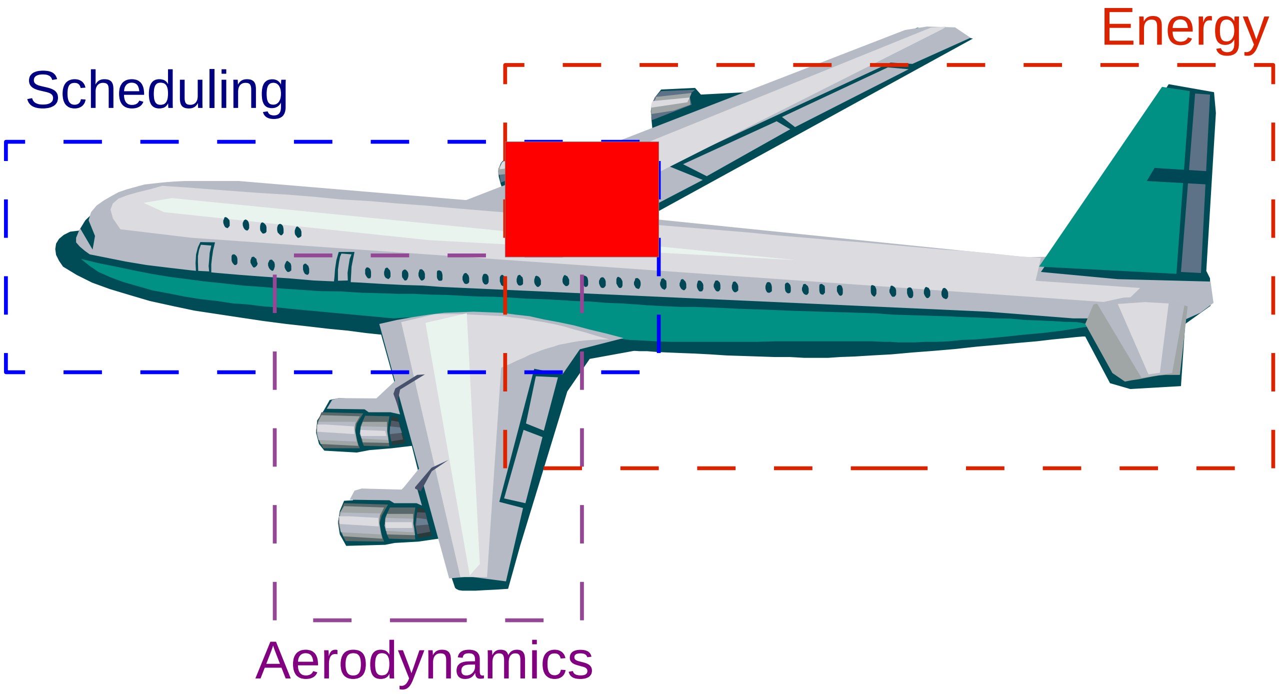
Outline

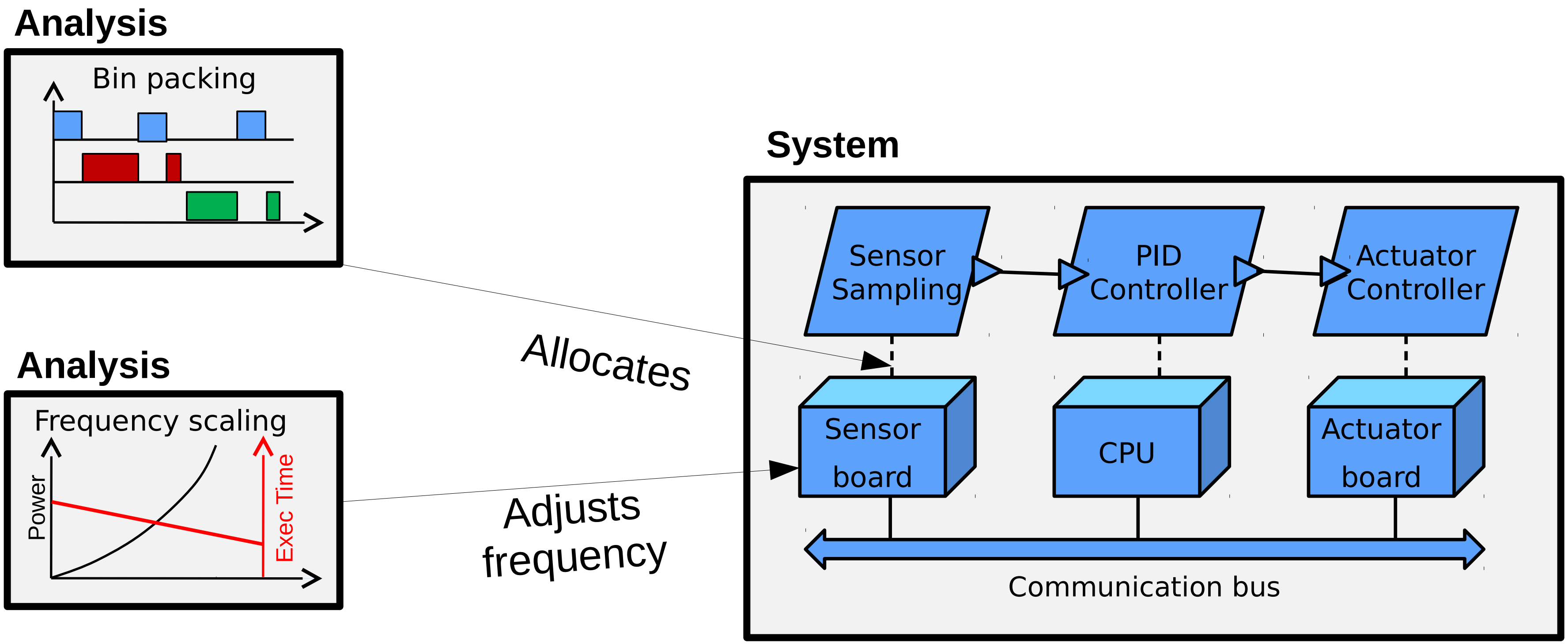
- Analysis integration problem
- Analysis contracts approach
  - Specification
  - Verification
- Experimental results

Model integration in CPS



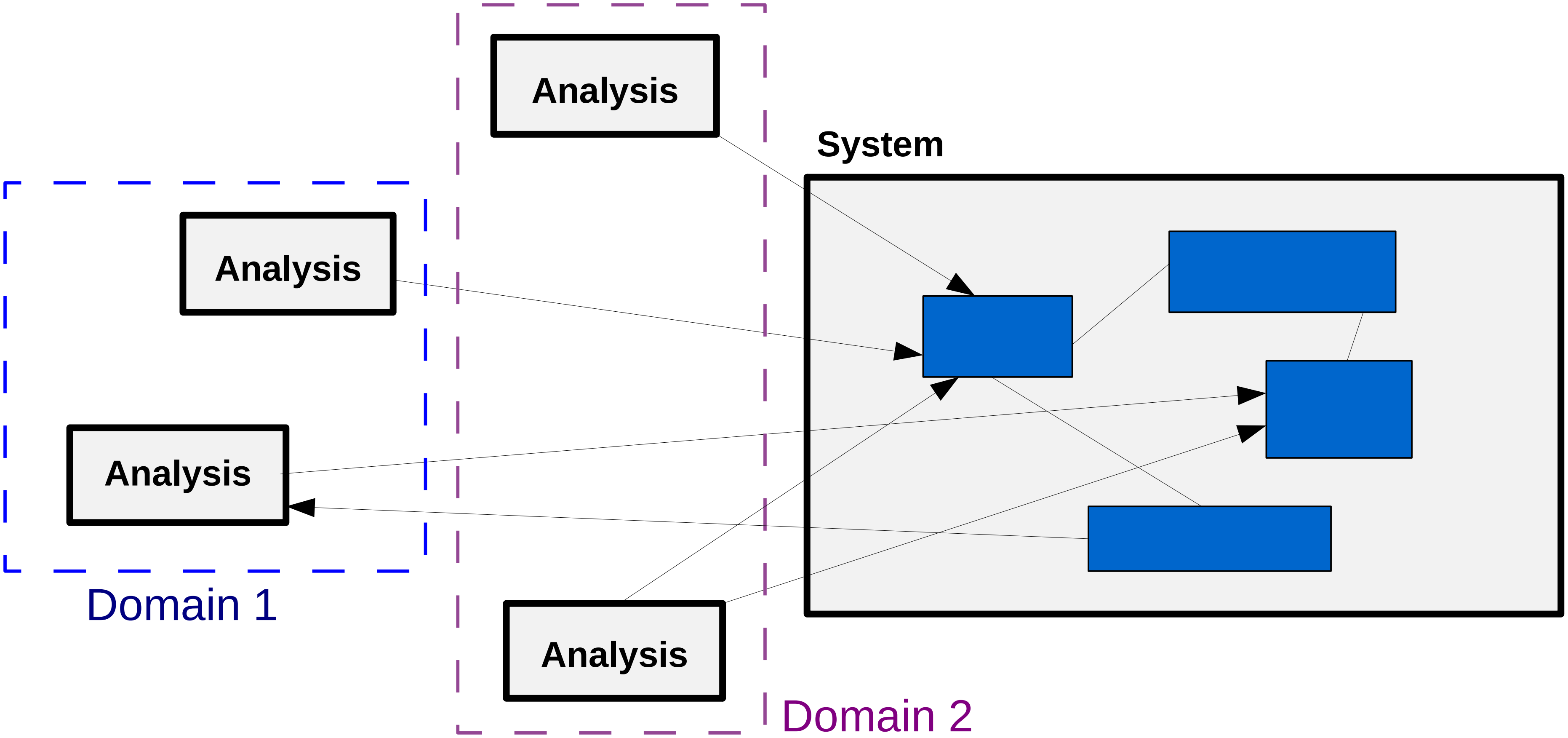
- Subtle mismatches between technical domains
- Lead to costly fixes or failures

Analytic aspect of integration



- Frequency scaling is applicable only when:
  - used after Bin packing
  - the system is behaviorally deadline-monotonic
- Otherwise, frequency scaling may render the system not schedulable
- Hence, model consistency is not sufficient

Analysis integration problem



- Out-of-order execution
- Invalidation of assumptions

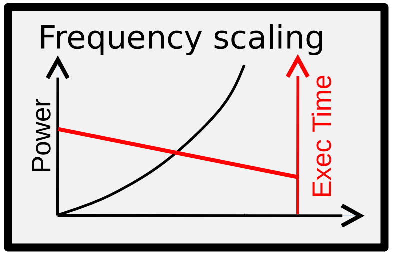
Existing solutions

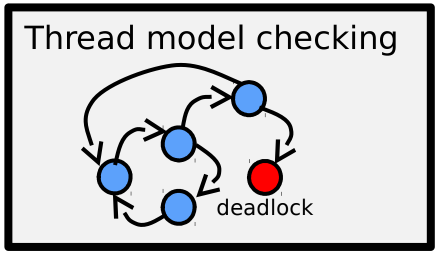
- Assume-guarantee component composition does not handle analytic integration of tools [1][2].
- Architectural views tackle model consistency, not analytic tool consistency [3][4]
- Meta-level AADL languages do not allow domain-specific semantics [5]
- Previous work on contracts: single domain only, unsound and incomplete verification [6]

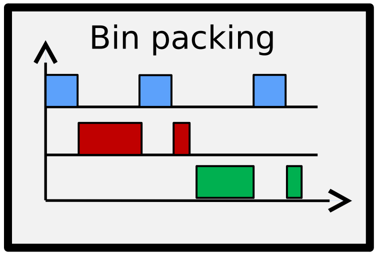
[1] Frehse et al. Assume-guarantee reasoning for hybrid I/O-automata by over-approximation of continuous interaction, 2004
[2] Sangiovanni-Vincentelli et al. Taming Dr. Frankenstein: contract-based design for cyber-physical systems, 2013
[3] Torngren et al. Integrating viewpoints in the development of mechatronic products, 2013
[4] Rajhans et al. Supporting heterogeneity in cyber-physical systems architectures, 2014
[5] Boddy et al. The FUSED meta-language and tools for complex system engineering, 2011
[6] Nam et al. Resource allocation contracts for open analytic runtime models, 2011

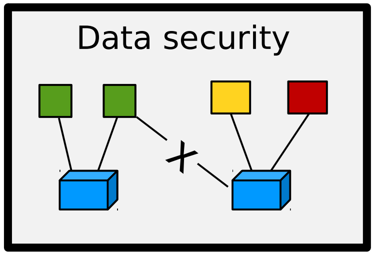
Running example

Scheduling

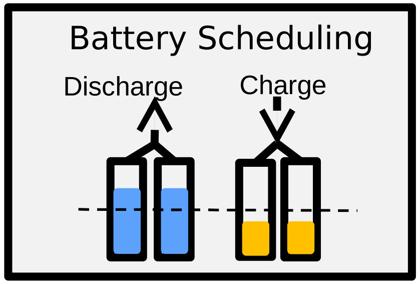


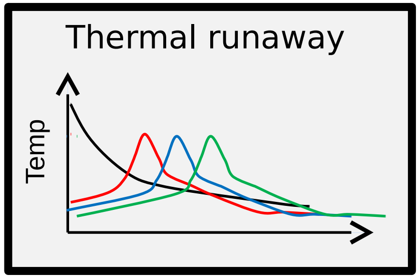




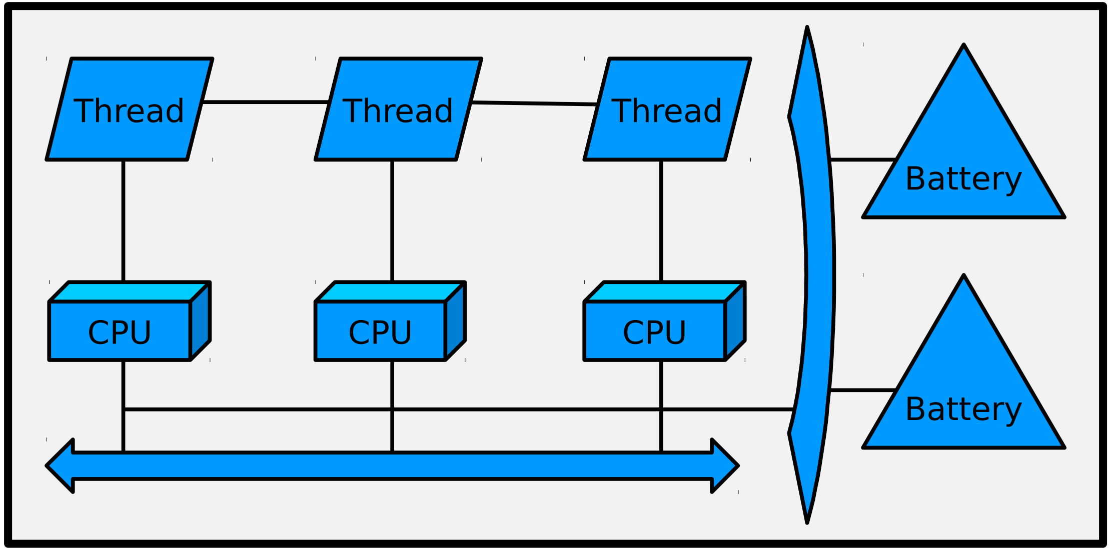


Battery





System



Outline

- Analysis integration problem
- **Analysis contracts approach**
  - Specification
  - Verification
- Experimental results

Analysis contracts approach

- Formalize analysis domains
- Specify dependencies and assumptions of analyses
- Determine correct ordering of analyses
- Verify assumptions of analyses

Outline

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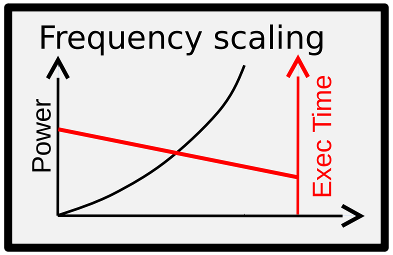
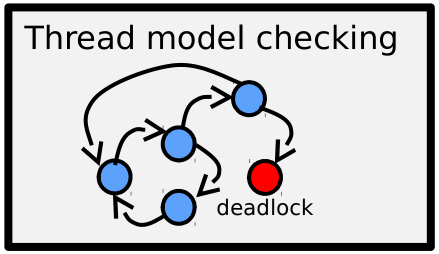
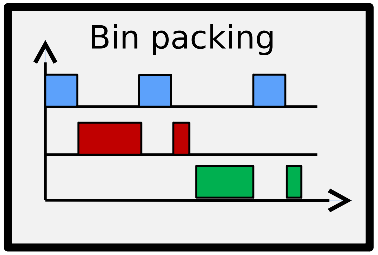
- Analysis contracts approach
  - **Specification**
  - Verification
- Experimental results

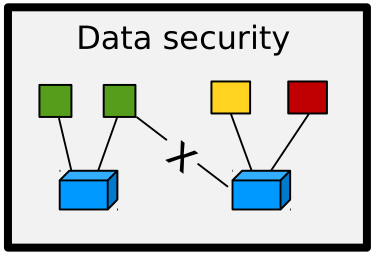
Running example

Scheduling

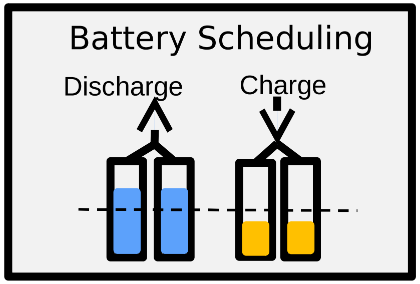

Frequency scaling

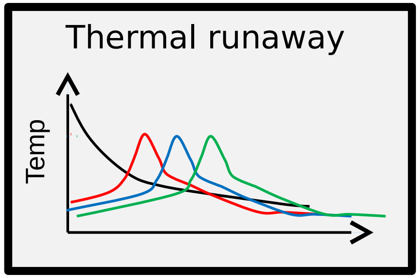

Thread model checking


Bin packing

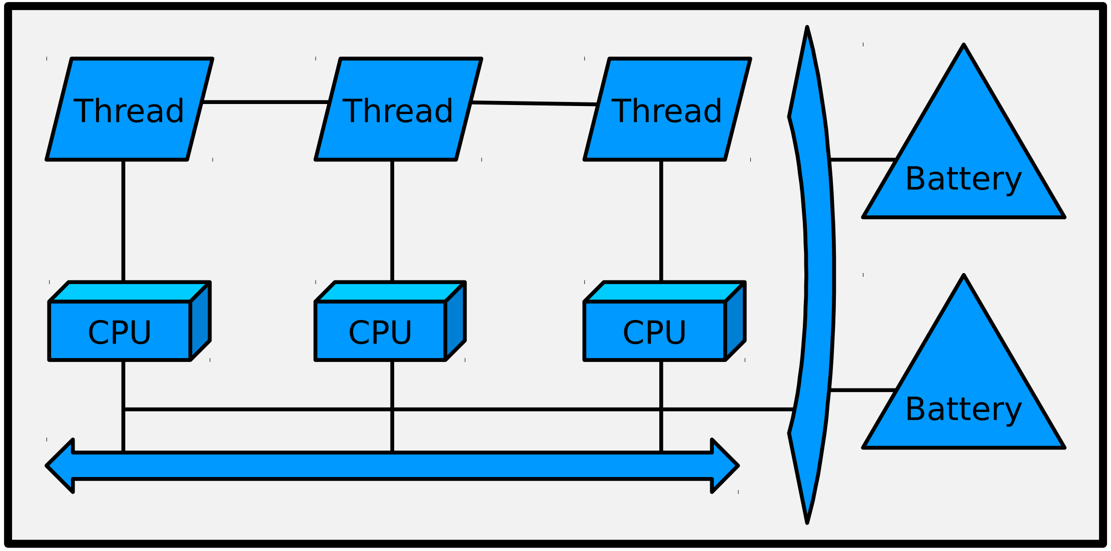

Data security

Battery


Battery Scheduling

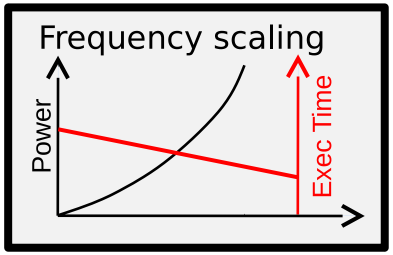

Thermal runaway

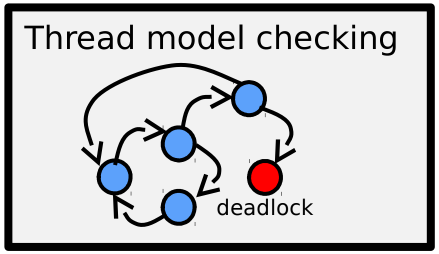
System

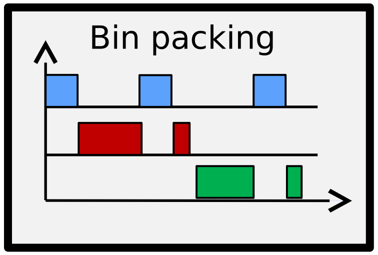


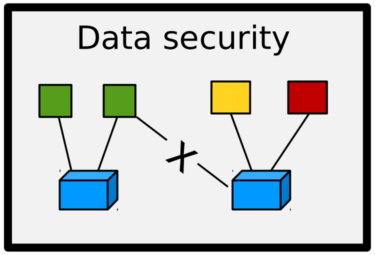
Verification domain

Scheduling domain $\boldsymbol{\sigma}_{\textbf{sched}}$

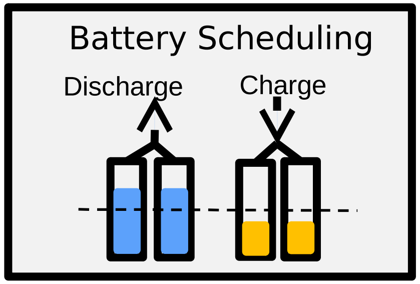


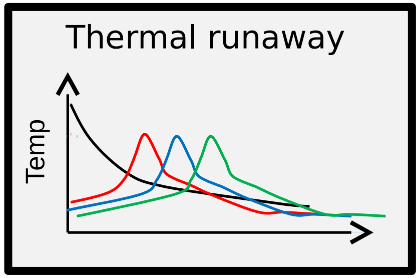




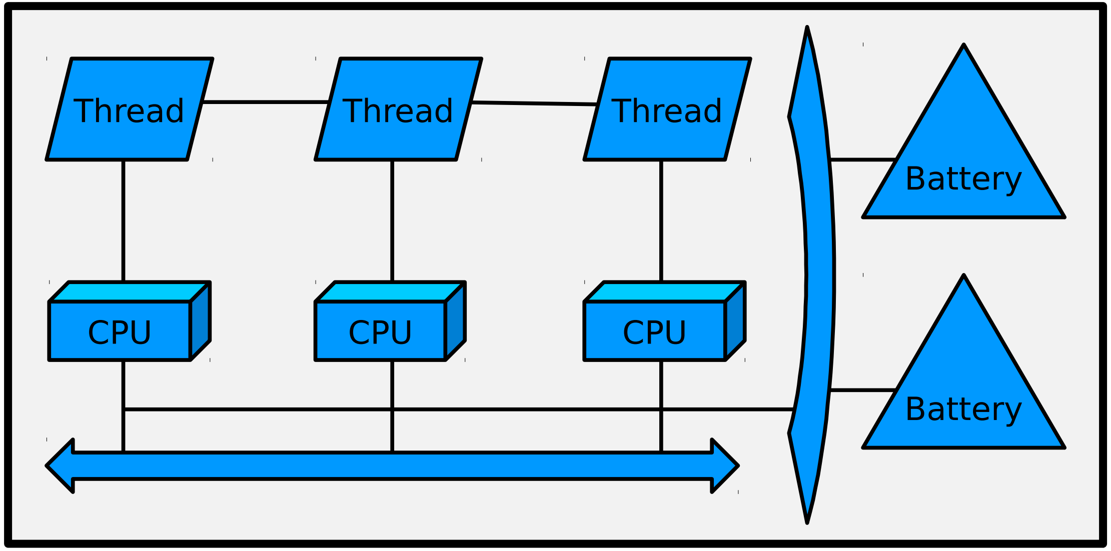


Battery domain $\boldsymbol{\sigma}_{\textbf{batt}}$





System



Verification domain

- Domain **σ** is a many-sorted signature ($\mathcal{A}$, $\mathcal{S}$, $\mathcal{R}$, $\mathcal{T}$, $\{\!\!\{\ \}\!\!\}_{\sigma}$):
  - $\mathcal{A}$: set of sorts – system elements and standard sorts
    - E.g.: $\mathbb{B}$, $\mathbb{Z}$, *Threads*, *Batteries, SchedPol*
  - $\mathcal{S}$: $\mathcal{A}_i$ x … x $\mathcal{A}_n$ → $\mathcal{A}_k$ – static functions that encode design properties
    - E.g.: *Period, Dline, CPUBind, Voltage*
  - $\mathcal{R}$: $\mathcal{A}_i$ x … x $\mathcal{A}_n$ → $\mathcal{A}_k$ – runtime functions that encode dynamic properties
    - E.g.: C*anPrmpt*: *Threads* x *Threads* → $\mathbb{B}$
      TN: *Batteries* x $\mathbb{Z}$ → $\mathbb{Z}$

Verification domain

- Domain $\boldsymbol{\sigma}$ is a many-sorted signature ($\mathcal{A}$, $\mathcal{S}$, $\mathcal{R}$, $\mathcal{T}$, $\llbracket\,\rrbracket_{\boldsymbol{\sigma}}$):
  - $\mathcal{T}$: execution semantics – set of sequences of $\mathcal{R}$ assignments
    - E.g.: thread scheduler state model for $\boldsymbol{\sigma}_{\textbf{sched}}$
      battery state model for for $\boldsymbol{\sigma}_{\textbf{batt}}$
  - $\llbracket\,\rrbracket_{\boldsymbol{\sigma}}$: domain interpretation for $\mathcal{A}$ and $\mathcal{S}$
    - E.g.: $\llbracket \mathit{SchedPol} \rrbracket_{\boldsymbol{\sigma}}$ = {RMS, DMS, EDF}
- Architectural model **m** is an interpretation $\llbracket\,\rrbracket_{\mathbf{m}}$ of $\mathcal{A}$, $\mathcal{S}$, and $\mathcal{T}$
  - E.g.: $\llbracket \mathit{Threads} \rrbracket_{\mathbf{m}}$ = { SensorSample, Ctrl_1, Ctrl_2 }
    $\llbracket \text{CPUBind} \rrbracket_{\mathbf{m}}$ **=** { (Ctrl_1, CPU_1), (Ctrl_2, CPU_2), … }
  - $\llbracket\,\rrbracket_{\boldsymbol{\sigma}} \cup \llbracket\,\rrbracket_{\mathbf{m}}$ is a full interpretation

Analysis contract

- Given a domain $\boldsymbol{\sigma}$, *analysis contract* **C** is a tuple (**I**, **O**, **A**, **G**)
  - Inputs $\mathbf{I} \subseteq \mathcal{A} \cup \mathcal{S}$
  - Outputs $\mathbf{O} \subseteq \mathcal{A} \cup \mathcal{S}$
  - Assumptions $\mathbf{A} \subseteq \mathcal{F}_{\boldsymbol{\sigma}}$
  - Guarantees $\mathbf{G} \subseteq \mathcal{F}_{\boldsymbol{\sigma}}$
- Where:
  - $\mathcal{F}_{\boldsymbol{\sigma}} ::= \{\forall|\exists\}\ v_1..v_n \bullet \boldsymbol{\varphi} \ \mid\ \{\forall|\exists\}\ v_1..v_n \bullet \boldsymbol{\varphi} : \boldsymbol{\psi}$
  - $\boldsymbol{\varphi}$ is a static logical formula over $\mathcal{A}$ and $\mathcal{S}$
  - $\boldsymbol{\psi}$ is an LTL formula over $\mathcal{A}$, $\mathcal{S}$, and $\mathcal{R}$
- $\mathcal{F}_{\boldsymbol{\sigma}}$ semantics is given in a standard way
  - **:** means ⇒ in case of ∀, and ∧ in case of ∃

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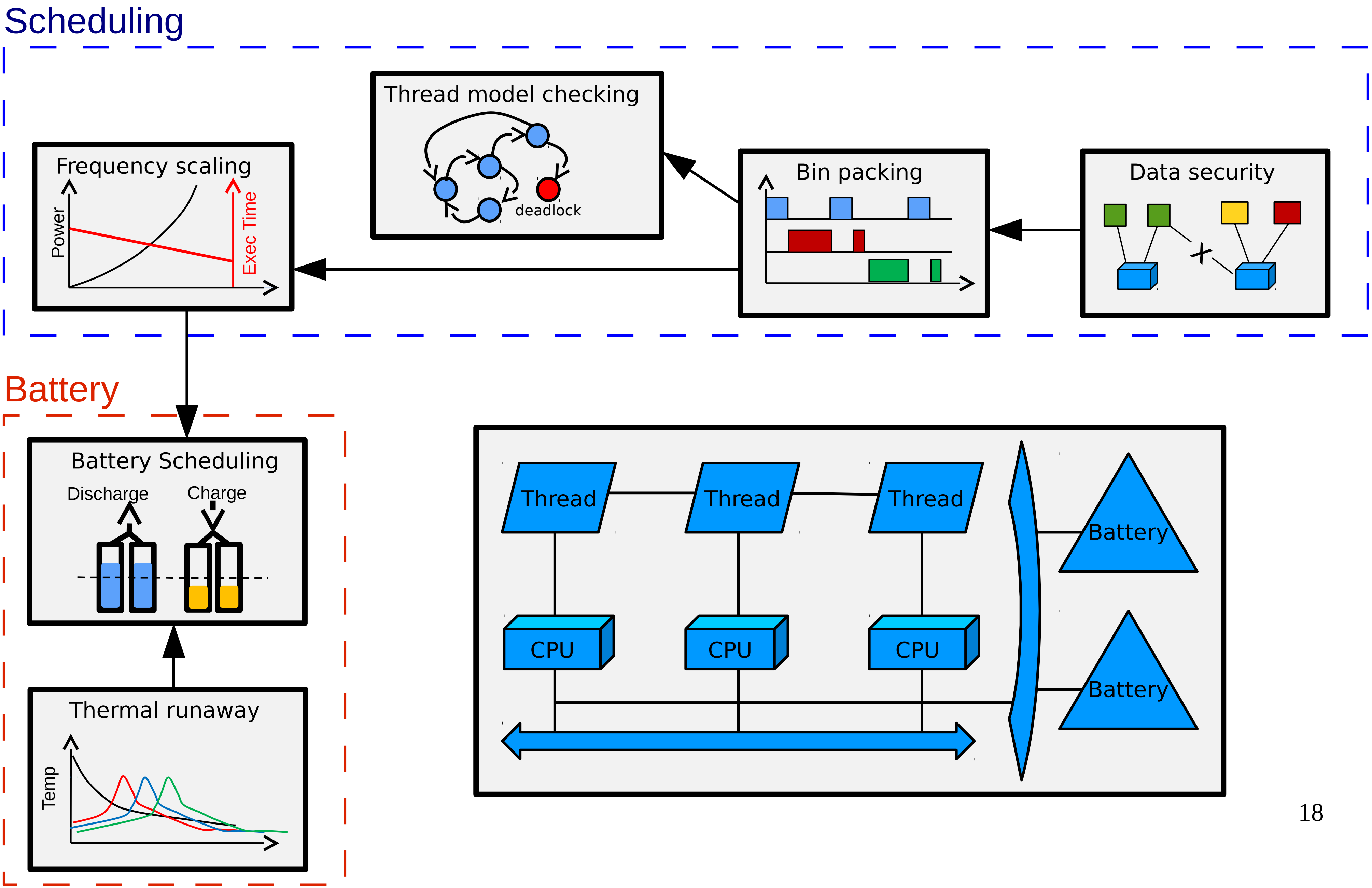
Contract I/O dependencies



Scheduling

Thread model checking

Frequency scaling

Bin packing

Data security

Battery

Battery Scheduling

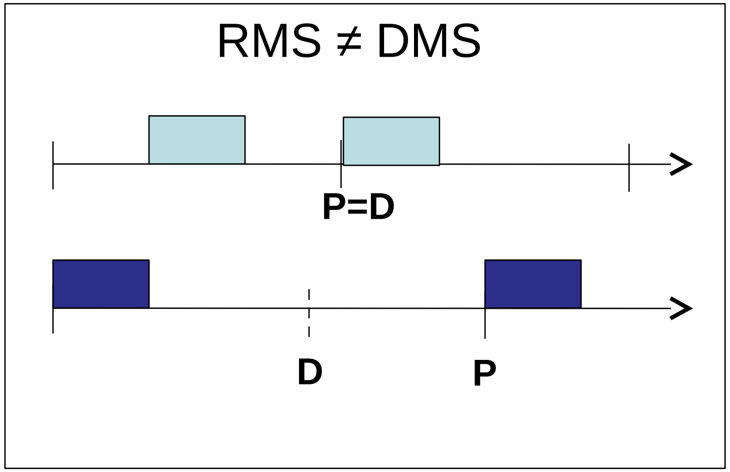
Thermal runaway

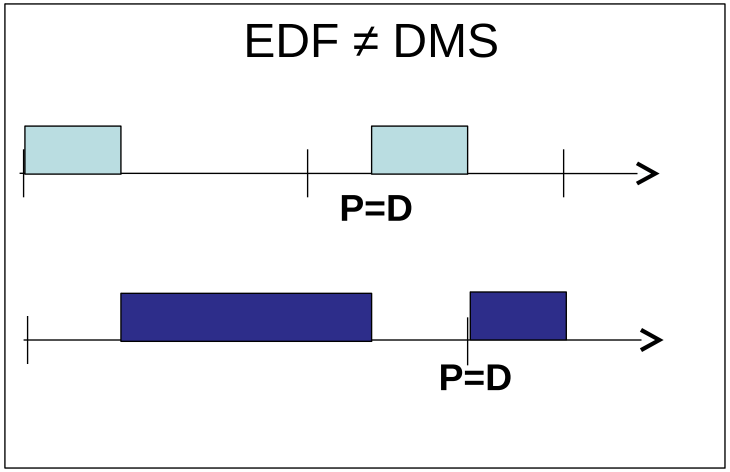
Frequency scaling assumption

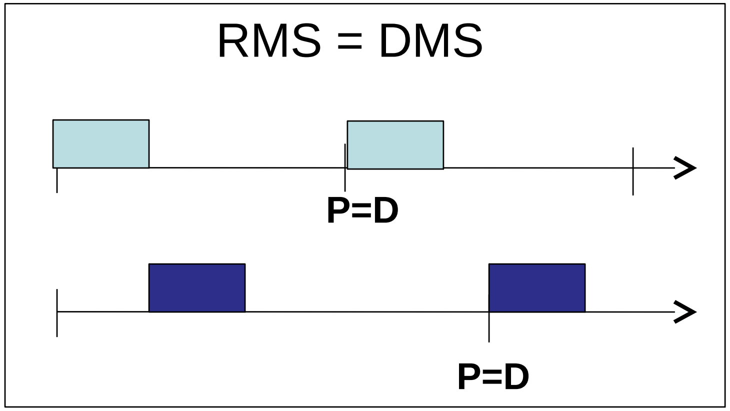
Behavioral equivalence to deadline-monotonic scheduling:

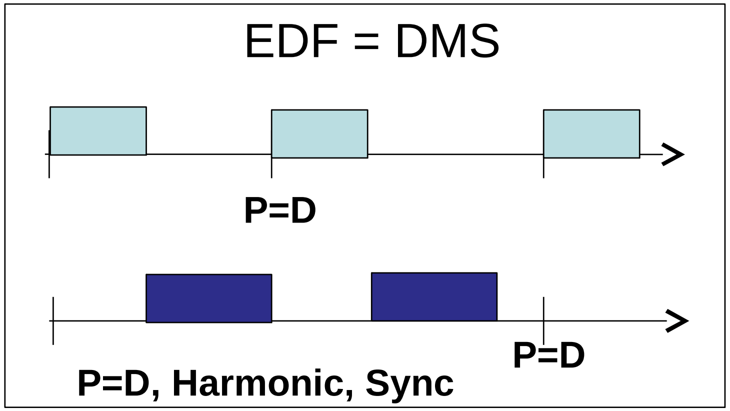
- $\forall\, t_1, t_2: \mathit{Threads} \bullet t_1 \neq t_2 \wedge \mathit{CPUBind}(t_1) = \mathit{CPUBind}(t_2)$:

  $G\ (\mathit{CanPrmpt}(t_1, t_2) \Rightarrow \mathit{Dline}(t_1) < \mathit{Dline}(t_2))$





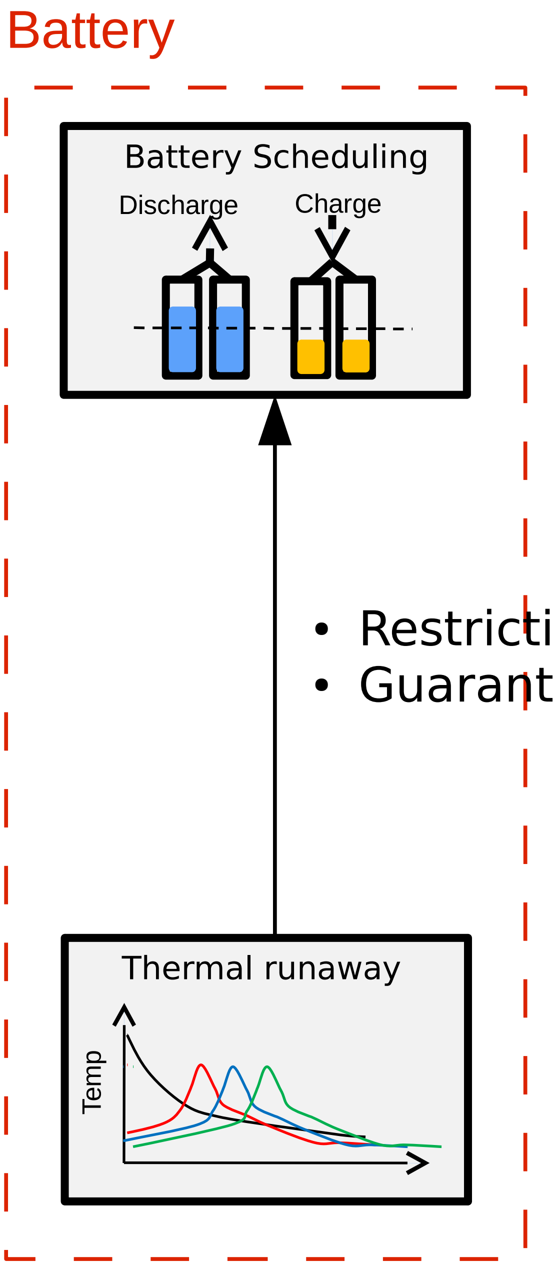




Assumption verification

- SMT solver finds solutions for static fragment $\boldsymbol{\varphi}$
  - $\forall$ t_1, t_2:*Threads* | $t_1 \neq t_2 \wedge$ *CPUBind*(t_1) = *CPUBind*(t_2)
- Model checking property $\boldsymbol{\psi}$ in a behavioral Promela model for each SMT solution:
  - G (*CanPrmpt*(t_1, t_2) $\Rightarrow$ *Dline*(t_1) < *Dline*(t_2))

Battery modeling



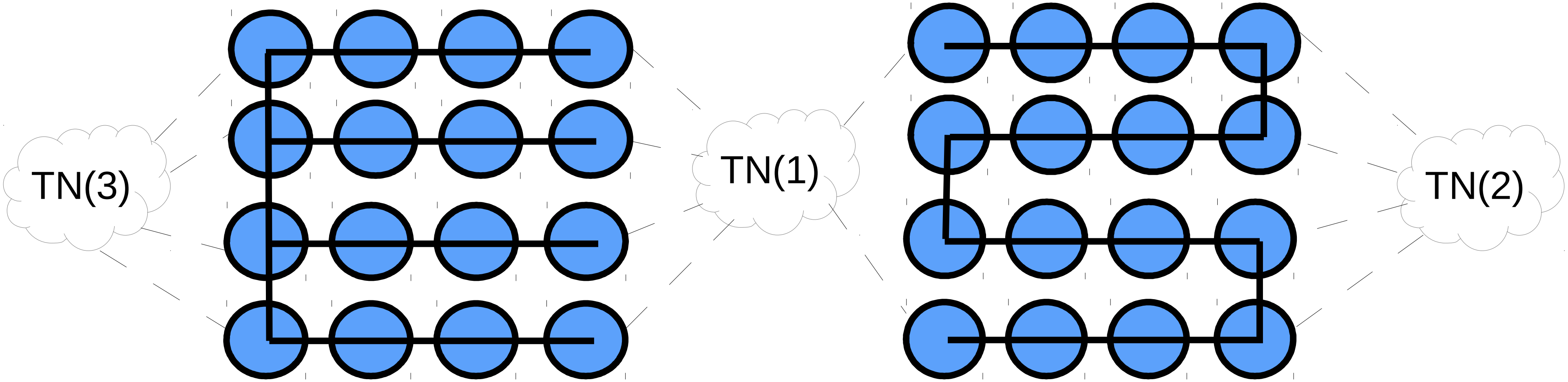
- Abstraction: circuits
- Selects a scheduler for cell connections
- Oblivious of heat: treats any configuration as acceptable heat-wise

- Restrictions on acceptable thermal configurations
- Guarantee: unacceptable ones don't occur

- Abstraction: geometry
- Simulates heat propagation
- Cannot scale to dynamic scheduling: simulates only fixed cell configurations

Battery scheduling guarantee

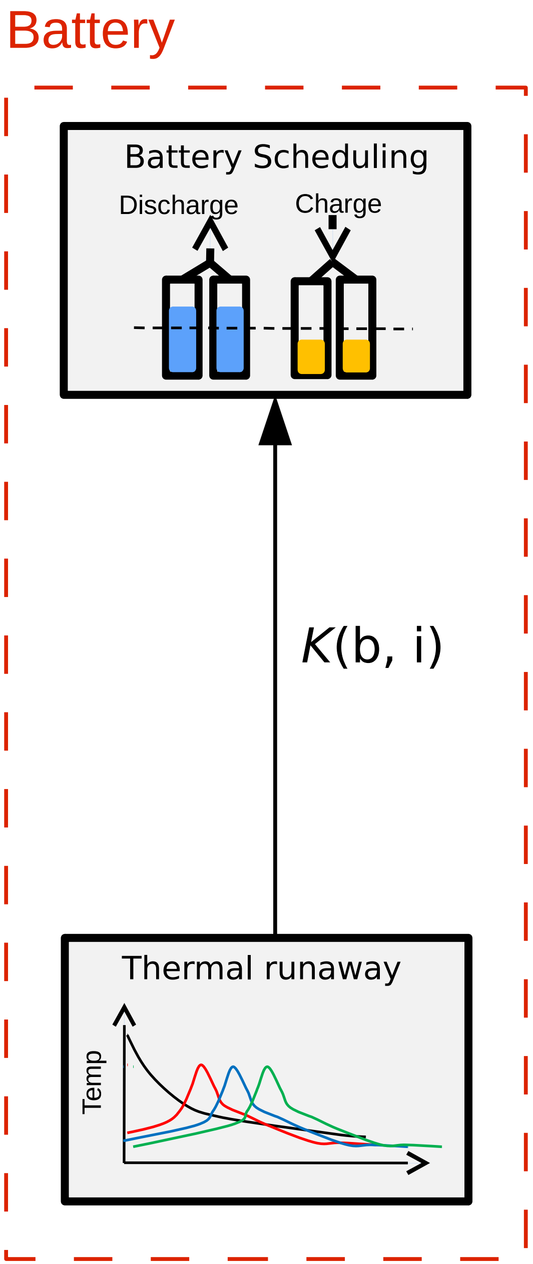
- “Bad” thermal configurations not reachable



- *TN*(b, i) ∈ $\mathcal{R}$ – number of cells in b with i thermal neighbors
- *K*(b, i) ∈ $\mathcal{S}$ – experimental coefficient for *TN*(b, i)
- Guarantee:

  ∀ b: *Batteries* • G ($\sum_{i=0..3}$ *K*(b, i)**TN*(b, i)) ≥ 0

Battery modeling



Selects a battery scheduler

Guarantee: $\forall$ b: *Batteries* • G ($\sum_{i=0..3}$ *K*(b, i)**TN*(b, i)) ≥ 0

Verified with battery Promela/Spin model

Determines *K*(b, i) via simulation

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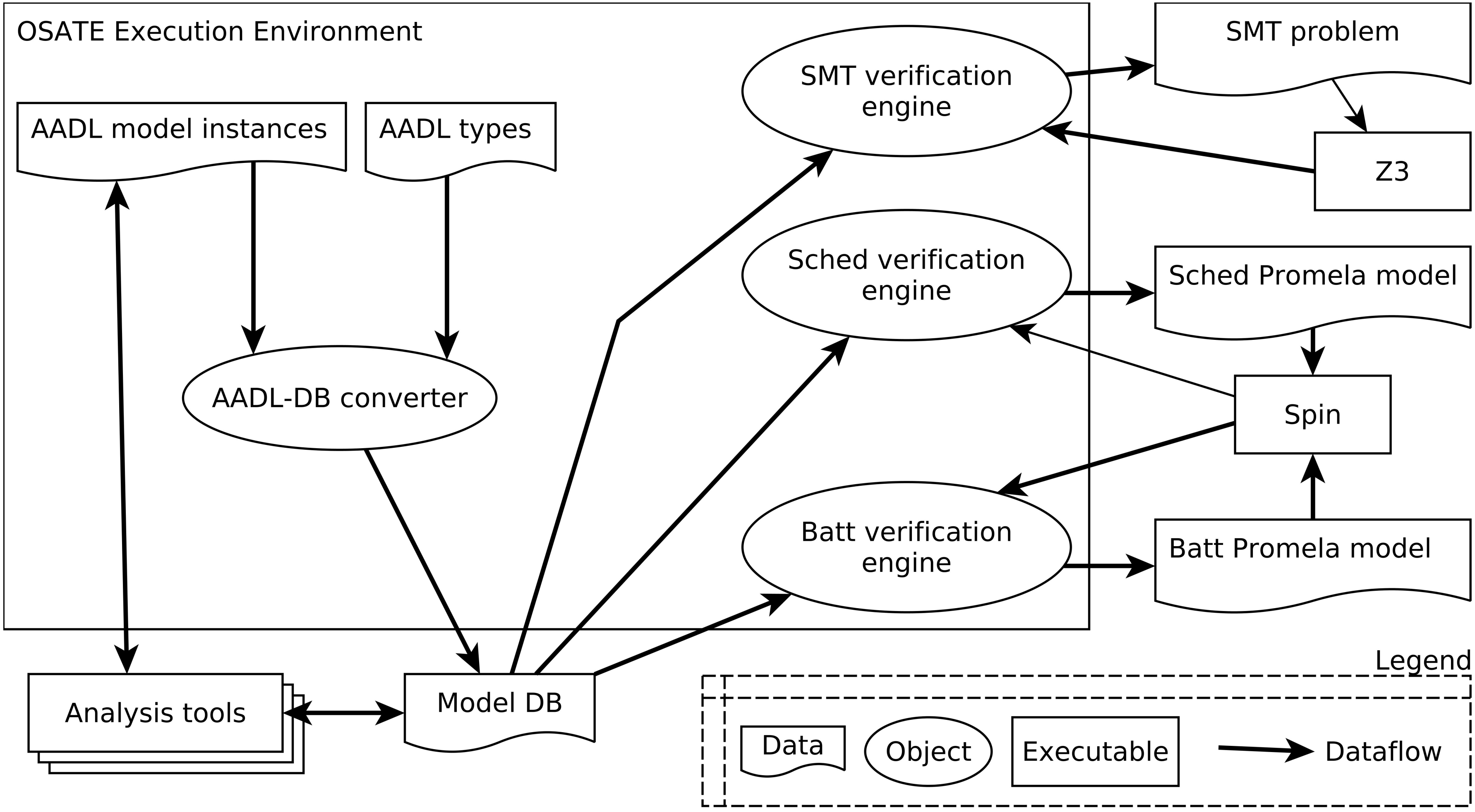
- **Experimental results**

Framework implementation



Scalability evaluation

- SMT solving typically takes less than 0.1 second
- Spin model checking times:

σ_{sched} :

Threads	(R/D)MS time	EDF time
3	0.01	0.01
4	0.01	0.52
5	0.07	33.4
6	0.37	2290.0
7	2.18	Out Mem
8	12.4	Out Mem
9	71.2	Out Mem
10	421	Out Mem
11	Out Mem	Out Mem

σ_{batt} :

Cells	FGURR time	FGWRR time	GPWRR time
9	0.13	0.15	0.15
12	0.61	2.34	3.94
16	44	31.4	127
20	1060	619	Out Mem
25	Out Mem	Out Mem	Out Mem

All times are in seconds

Summary

- Analysis integration is error-prone
  - Incorrect ordering
  - Violation of implicit assumptions
- Our solution:
  - Contract specification language
  - Contract verification algorithm
- Effective, extensible, and scalable
- Future work:
  - Assumptions behind $\mathcal{I}$ implementation
  - Analysis contracts for multiple views

Contracts

Security Analysis

- $An_{sec}\,.\,C\colon I = \{T, \mathit{ThSecCl}\}, O = \{\mathit{NotColoc}\}, A = \emptyset, G = \{g\}$
  - $g\colon \forall\, t_1, t_2 \cdot \mathit{ThSecCl}(t_1) \neq \mathit{ThSecCl}(t_2) \Rightarrow t_1 \in \mathit{NotColoc}(t_2)$

Multiprocessor scheduling: (Binpacking + scheduling)

- $An_{sched}.\,C\colon I = \{T, C, \mathit{NotColoc}, \mathit{Per}, \mathit{WCET}, \mathit{Dline}\}, O = \{\mathit{CPUBind}\}, A = \emptyset, G = \{g\}$
  - $g\colon \forall\, t_1, t_2 \cdot t_1 \in \mathit{NotColoc}(t_2) \Rightarrow \mathit{CPUBind}(t_1) \neq \mathit{CPUBind}(t_2)$

Frequency Scaling

- $An_{freqsc}.\,C\colon I = \{T, C, \mathit{CPUBind}, \mathit{Dline}\}, O = \{\mathit{CPUFreq}\}, G = \emptyset, A = \{a\}$
  - $a\colon \forall t_1, t_2 \cdot \mathit{CPUBind}(t_1) = \mathit{CPUBind}(t_2)\colon G(\mathit{CanPrmpt}(t_1, t_2) \Rightarrow \mathit{Dline}(t_1) < \mathit{Dline}(t_2)$

Model checking periodic program (REK):

- $An_{rek}.\,C\colon I = \{T, C, \mathit{Per}, \mathit{Dline}, \mathit{WCET}, \mathit{CPUBind}\}, O = \{\mathit{ThSafe}\}, G = \emptyset, A = \{a_1, a_2\}$
- $a_1\colon \forall t \cdot \mathit{Per}(t) = \mathit{Dline}(t),\;\; a_2\colon \forall t_1, t_2 \cdot G(\mathit{Canprmpt}(t_1, t_2) \Rightarrow G\ \neg \mathit{CanPrmpt}(t_2, t_1))$

Thermal runaway:

- $An_{therm}.\,C\colon I = \{B, \mathit{BatRows}, \mathit{BatCols}, \mathit{Voltage}\}, O = \{K\}, A = \emptyset, G = \emptyset$

Battery Scheduling

- $An_{bsched}.\,C\colon I = \{B, \mathit{BatRows}, \mathit{BatCols}\}, O = \{\mathit{BatConnSchedPol}, \mathit{HasReqLifetime}, \mathit{SeriqlReq}, \mathit{ParalRea}\}, A = \emptyset, G = \{g\}$
- $g\colon G(K(0) \times TN(0) + K(1) \times TN(1) + K(2) \times TN(2) + K(3) \times TN(3) \geq 0)$